Published in IET Microwaves, Antennas & Propagation
Received on 6th May 2009
Revised on 29th January 2010
doi: 10.1049/iet-map.2009.0280

In Special Issue on Selected Papers from Mosharaka International Conference on Communications, Propagation and Electronics (MIC-CPE 2009)

ISSN 1751-8725

Improving the chromatic dispersion tolerance in long-haul fibre links using the coherent optical orthogonal frequency division multiplexing

M.A. Jarajreh Z. Ghassemlooy W.P. Ng

NCR Lab, Optical Communications Research Group, School of Computing, Engineering and Information Sciences, Northumbria University, Newcastle NE1 8ST, UK
E-mail: mutsam.jarajreh@northumbria.ac.uk

Abstract: Numerical simulations of the coherent optical orthogonal frequency division multiplexing modems are undertaken to investigate the effect of the adaptive modulation, the number of sub-carriers, the cyclic prefix (CP) length, the clipping ratio, quantisation bit resolution and the sampling speed of analogue-to-digital converters (ADCs) on the chromatic dispersion (CD) of a single mode fibre (SMF) at data rates up to 80 Gbps. The use of a large number of sub-carriers is more effective in combating fibre dispersion than employing a long CP; moreover, the optimum number of sub-carriers in the presence of both SMF non-linearities and CD has been identified. The authors show that using a high bit resolution ADC with a high clipping ratio, the transmission distance can be increased at specific data rates. Furthermore, it is shown that ADCs with a low sampling speed also improve the system tolerance to the fibre CD. In addition, simulation results show that the use of adaptive modulation schemes improves spectrum usage efficiency, thus resulting in higher tolerance to the CD when compared with the case in which identical modulation formats are adopted across all sub-carriers.

1 Introduction

In recent years, there is a growing interest in applications of orthogonal frequency division multiplexing (OFDM) in mobile communication systems. OFDM is a robust, cost-effective and flexible scheme with high resilience to multipath induced inter-symbol interference (ISI), thus offering an improved transmission performance [1]. In [2–4], its optical version, that is, optical OFDM (OOFDM), has been adopted for high-speed long-haul optical fibre communication links to combat fibre-induced chromatic dispersion (CD), polarisation mode dispersion (PMD) and a high spectral efficiency. According to its applications, OOFDM can be sub-categorised into two main groups: (1) the intensity modulation/direct detection (IM/DD) used in local and access networks [5] and (2) coherent OOFDM (CO-OOFDM), which is utilised in long and ultra-long-haul optical networks offering superior performance in spectral efficiency, receiver sensitivity and PMD [6]. The main challenges for high-speed long distance optical communication systems are the CD and fibre non-linearities. To address these technical challenges, especially for the CO-OOFDM modem, a number of CD compensation schemes have been proposed. In [7, 8], transmission of optical single side band signals, which ensures transfer of optical phase into the electrical domain, allows linear electronic filters to be used for CD compensation. Several digital signal processing-based schemes including electronic pre-distortion at the transmitter [9], the maximum-likelihood sequence estimation [10] and the coherent phase and polarisation diversity reception [11] have been adopted for CD compensation. In long-haul optical system fibre, non-linearity is a major problem, unless the optical power is kept at a low level [12]. Electronic pre-compensation approach has been applied for the compensation of fibre non-linearities [13] and for PMD [14]. In [15], a simple signal processing at the transmitter in the CO-OFDM system adopted for CD compensation has been used to mitigate fibre non-linearities.

In wavelength division multiplexing (WDM) systems, spectral efficiency is an important factor. In OOFDM schemes, which are essentially an optical equivalent of the radio frequency OFDM, the spectral efficiency of ~1 bit/s/Hz, in principle, could be achieved by utilising the orthogonality between the spectral profiles of each channel. In [16, 17], it has been shown that a CO-OFDM modulation format employing a cyclic prefix (CP) can tolerate fibre CD equivalent to 3000 km standard single mode fibre (SMF) and is also robust against the second-order PMD.

As the CP duration is determined by the system designer, consequently selecting a CP time duration smaller than the CD associated with an SMF link will limit the maximum achievable transmission performance of the CO-OOFDM. In contrast, if CP is longer than the CD for a fixed signal sampling rate, then the system optical signal-to-noise ratio (OSNR) will degrade because of the large amount of power being used by the CP signal. For a fixed sampling speed, utilising a large number of sub-carriers in one CO-OOFDM symbol will increase the CO-OOFDM symbol length and consequently the time duration of the CP, thus leading to enhanced tolerance to the fibre CD and to improved transmission performance. By choosing the guard interval between CO-OFDM symbols (frames) to be larger than the CD-induced delay spread, the ISI can also be removed completely [16]. With a high peak-to-average-power ratio, the OFDM signal is more sensitive to non-linearity induced by the external modulator, particularly at higher modulation indices than the IM/DD scheme [18]. In IM/DD optical systems, optical source-related distortion levels can be controlled via careful setting of the bias point and backing off the OFDM signal power. Whereas in externally modulated optical systems, the fibre non-linearities can be controlled via small modulation index but at the cost of increased modulation insertion loss [18].

The analogue-to-digital converter (ADC) is one of the crucial devices for the OFDM real-time implementation. ADCs and digital-to-analogue converters (DACs) sampling speed, signal clipping and quantisation levels affect the system tolerance to the CD and the overall system performance. In [19], it is shown that the combination of an adaptive modulated OOFDM and an adaptive CP can improve the transmission performance over multimode fibre links for the IM/DD OFDM schemes. However, adopting identical modulation formats for all CO-OOFDM sub-carriers may result in some sub-carriers suffering from higher distortion levels than the others because of the frequency response of the SMF link. Therefore it is advantageous to employ dissimilar modulation formats on each sub-carrier depending on the link frequency response. However, the effects of CO-OOFDM modem parameters (i.e. number of sub-carriers, CP length, sampling speed and adaptive modulation) on the CD compensation tolerance for SMF links and transmission performance over SMF links have not been reported by researchers. The authors investigate the capability of the adaptive modulated CO-OOFDM schemes for the compensation of the CD and fibre non-linearities. Moreover, the impact of the CO-OOFDM above-mentioned parameters on the CD tolerance for CO-OOFDM signals transmitted over an SMF link for different modulation schemes is also investigated.

The rest of the paper is organised as follows: in Section 2, the CO-OOFDM modem design is outlined with the corresponding simulation parameters. Section 3 investigates and compares the effect of number of sub-carriers and CP on the CD tolerance and the optimum number of sub-carriers while transmitting over SMF links. Sections 4 and 5 investigate the effect of sampling and adaptively modulated CO-OOFDM on the CD tolerance and transmission performance. Finally, the paper is concluded in Section 6.

2 System model

Fig. 1 shows a top level block diagram of a CO-OOFDM modem adopted in the numerical simulation. At the transmitter side, the complex valued data streams are passed through a serial-to-parallel converter producing an $N \times 1$ vector $\boldsymbol{X}_n$ prior to being mapped into N_d constellation symbols $\{\boldsymbol{X}[k]\}_{k=0}^{N_d'-1}$ using a number of modulation schemes, including differential binary phase shift keying (DBPSK), differential quadrature phase shift keying (DQPSK), 16-quadrature amplitude modulation (QAM), 32-QAM, 64-QAM, 128-QAM and 256-QAM. The data symbol is converted into a time domain CO-OFDM symbol by N orthogonal sub-carriers by means of an inverse fast Fourier transform (IFFT) given as

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \boldsymbol{X}[k] e^{j2\pi nk/N}, \quad n = 0, \ldots, N-1 \qquad (1)$$

The nth OFDM symbol is constructed by adding a CP of length G samples, which is added to x_n, the parallel symbols of the IFFT, before being serialised to form a long digital complex data sequence. The in-phase (I) and quadrature (Q) components of the data sequence are separated and subsequently applied to DACs. The outputs of DACs are applied to two identical Mach–Zehnder modulators with an integrated laser source at a wavelength of 1554.94 nm biased at zero output power and a 90° phase shifter. Finally, the optical signal propagating through an SMF is amplified using a number of erbium-doped fibre amplifiers (EDFAs) at a regular interval to cover the total link span.

At the receiver side, the CO-OOFDM signal is detected using two identical optical coherent balanced detectors

doi: 10.1049/iet-map.2009.0280

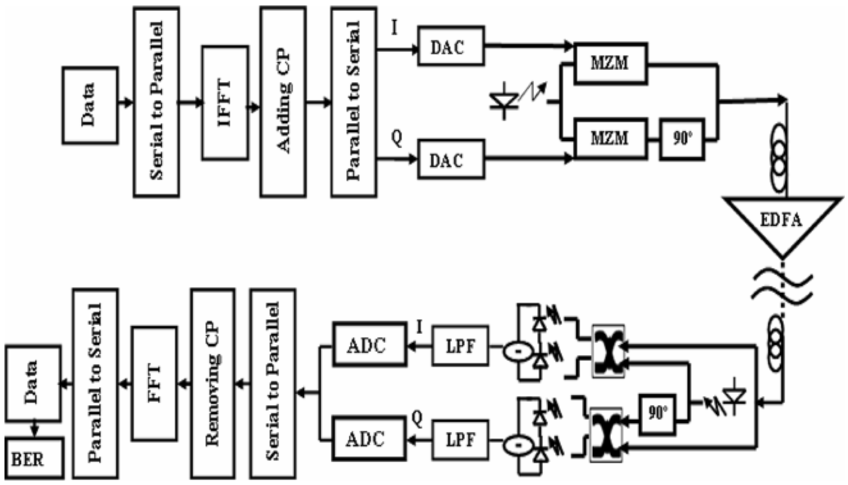

Figure 1 *Baseband model of CO-OOFDM adopted for numerical simulations*

acting as an optical-to-electrical OFDM I/Q converter, in which I/Q components of a locally generated carrier are mixed with the optical signal to obtain the electrical I/Q components. Each coherent detector consists of a pair of couplers and PIN detectors [20]. The low-pass filters transfer functions and attenuate the sub-carriers close to the Nyquist frequency, thus reducing the usable bandwidth as the attenuated sub-carriers cannot be used for data transmission. The outputs of DACs are passed through a serial–parallel module prior to removing the CP. Owing to the CP, the linear convolution between the transmitted signal and the channel becomes a circular convolution; hence, the output of the FFT can be written as a product in the matrix form given by [21]

$$\boldsymbol{Y}_n = \mathrm{diag}\,(\boldsymbol{X}_n)\cdot \boldsymbol{H}_n + \boldsymbol{W}_n \tag{2}$$

where $\boldsymbol{H}_n = \boldsymbol{F}_n{\cdot}h_n$ is the frequency response of the channel with the length L, $[\boldsymbol{F}]_{n,k} = N^{-(1/2)}e^{-(j2\pi kn/N)}$ the FFT matrix, $\boldsymbol{W}_n$ the $N \times 1$ vector of the white Gaussian noise with $E[\boldsymbol{W}_n\boldsymbol{W}_n^H] = \sigma_n^2 I_N$ [8], $\boldsymbol{H}_n$ the $N \times 1$ vector, h_n the channel response, N the number of equally spaced sub-carriers at frequencies of $(k-0.5N)B/N$, B the OFDM bandwidth, $\boldsymbol{H}$ the Hermitian transpose and diag the diagonal matrix. An FFT followed by a parallel-to-serial converter is used to recover the original data. Note that $\boldsymbol{H}_n$ and $\boldsymbol{W}_n$ are statistically independent.

To set the OSNR to a specified value, an optical noise loading module (with a variable noise figure) is employed at the receiver to simply saturate the optical amplifier. This module can be modelled as an optical attenuator followed by a gain block. Having described CO-OOFDM modem and SMF-based coherent transmission link, this section details the parameters adopted in the numerical simulations. The simulation was performed using the MATLAB software, and all the key parameters adopted throughout the simulation are given in Table 1. Parameters not included in Table 1 will be addressed explicitly in the corresponding sections. In the next sections, we investigate the effects of the number of sub-carriers and CP and the ADC sampling speed on the CP tolerance and link transmission performance.

3 Simulation results

3.1 *Number of sub-carriers and CP effect on CD*

As discussed earlier, both the number of sub-carriers and the CP length do affect the CO-OOFDM signal tolerance to the CD in SMF links. The CP acts as a guard interval to avoid dispersion and is realised by repeating the last G samples of the OFDM symbol at the beginning so that $N+G$ samples are transmitted. To highlight such effects, numerical simulations are performed by setting the ADC (DAC) quantisation bits and the clipping ratio to be 10 and 13 dB, respectively. Here the dispersion tolerance and the transmission span are defined as the maximum fibre length at which a 1 dB increase in $\mathrm{OSNR}_{\min}$ is required with respect to the required $\mathrm{OSNR}_{\min}$ for the back-to-back case.

Fig. 2 shows the system capacity against the link span for a range of sub-carriers and CP for an SMF link with the CD only. Simulations reveal that for a fixed sampling speed, increasing the number of sub-carriers from 32 to 128 will increase the CO-OOFDM symbol and consequently the time duration of the CP, thus leading to enhanced tolerance to the fibre CD and to improved transmission performance. At 80 Gbps and for a CP of 25%, the increase in the link span is from 104 to 600 km (a factor of up to 5.7). However, for a fixed number of sub-carriers, dispersion tolerance can also be increased by increasing the CP length. As shown in Fig. 2 for 32 sub-carriers, increasing the CP length from 25 to 100% can improve the dispersion tolerance by a factor of 2.7 for lower data rates of up to 25 Gbps. However, for higher data rates, increasing the CP length will require employing higher modulation formats to achieve the same data rate when

Table 1 Simulation parameters

Parameters	Values
no. of sub-carriers	64
wavelength, nm	1550
light source	ideal laser diode
photodetector	PIN
photodetector responsivity	0.9
total fibre span, km	80–4480
chromatic dispersion, ps/nm/km	17
fibre loss, dB/km	0.2
ADC/DAC	
sampling rate, GS/s	12.5
clipping ratio, dB	13
quantisation, bits	10
Data rates	
DBPSK, Gb/s	10
DQPSK, Gb/s	20
16-QAM, Gb/s	40
32-QAM, Gb/s	50
64-QAM, Gb/s	60
128-QAM, Gb/s	70
256-QAM, Gb/s	80
low-pass filter order and 3 dB bandwidth, GHz	second and 6.5
EDFA span, km	80
EDFA gain, dB	16
EDFA noise figure, dB	6
CO-OFDM frame period, ns	6.4
length of CP	25% of the frame period, 1.28 ns

employing CP with reduced length. This is the reason behind the low impact of increasing the CP length for the above-mentioned condition. The physical reason behind the ability of the CP length to combat dispersion in SMF links is as follows: CO-OOFDM symbols transmitted over a dispersive link will experience a frequency-dependent delay, and consequently, the slow sub-carriers will cross the symbol boundary, thus leading to the ISI. Moreover, this can annihilate the orthogonality between the adjacent sub-carriers, thus resulting in the inter-carrier interference (ICI) [4]. Therefore a longer CP length helps in maintaining the orthogonality between the sub-carriers and in combating both the ISI and the ICI, but at the cost of reduced OSNR.

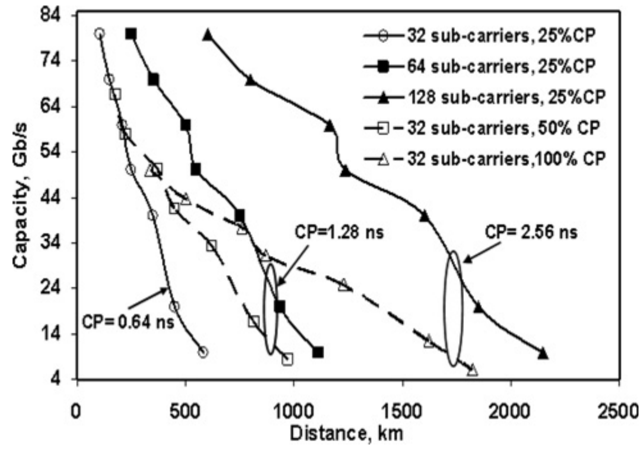

Figure 2 *Capacity against the link span for a range of sub-carriers and CPs*

In comparison with employing a long CP, the use of a large number of sub-carriers is more effective in combating fibre dispersion. This is because increasing the number of sub-carriers will enlarge the CP length. Moreover, for a fixed sampling frequency, increasing the number of sub-carriers reduces the frequency spacing between them, thus making the OFDM closely packed with a little walk-off due to dispersion between the sub-carrier signals propagating down a fibre [15]. However, a low walk-off will cause the effect of fibre non-linearities to be strong. Without any non-linearity compensation, fibres with a low CD suffer the greatest Q factor (note $\mathrm{BER} = P_e(q)$ and $Q = 20\log_{10}(q)$), whereas for fibres with a high CD (i.e. 16–17 ps/nm/km, used here), the Q factor is almost the same (i.e. ~14 dB) with and without pre-compensation [15].

3.2 Number of sub-carriers effect on transmission performance over SMF

Having investigated the effect of the number of sub-carriers on the dispersion tolerance, here the impact of the number of sub-carriers on the modem performance in the presence of fibre non-linearities is studied. The impact of the number of sub-carriers on CO-OOFDM modem signals transmitted over SMF links is shown in Fig. 3, in which the signal data rate is plotted as a function of transmission distance for a number of sub-carriers. It is shown that increasing the number of sub-carriers improves the data rate for the link length greater than 300 km. This improvement can be explained by considering the fact that for a fixed ADC sampling rate, the duration of the CP length increases with the number of sub-carriers, thus leading to the enhanced dispersion tolerance. In addition, for a fixed bandwidth, increasing the number of sub-carriers reduces the frequency spacing between the adjacent sub-carriers. This may induce sub-carrier intermixing effect if perfect orthogonality cannot be maintained between sub-carriers [15, 22]. For 10 Gbps data rate, the link length increases by 500 km every time the number of sub-carriers is doubled. This is may be due to the modulation formats

IET Microw. Antennas Propag., 2010, Vol. 4, Iss. 5, pp. 651–658
doi: 10.1049/iet-map.2009.0280

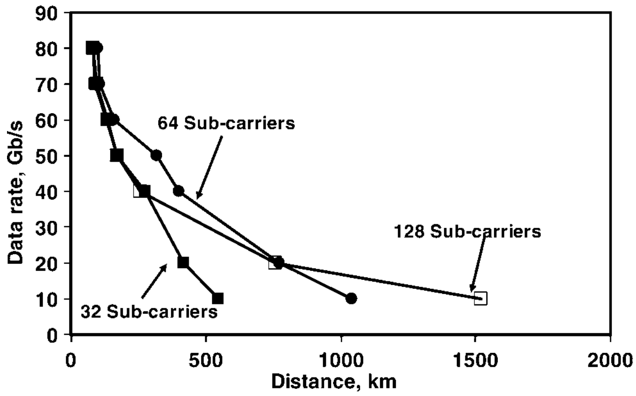

Figure 3 *Effect of number of sub-carriers on the transmission performance over SMF links*

such as DBPSK maintaining the orthogonality and combating the fibre non-linearity. For data rates >10 Gbps, using 128 sub-carriers will degrade the modem performance when compared with 64 sub-carriers. The frequency spacing between the adjacent number of sub-carriers decreases because of the increasing intermixing effect. Consequently, 64 sub-carriers can be considered as the optimum number of sub-carriers for the CO-OOFDM modems.

4 ADC sampling speed

It is well known that ADC's sampling speed plays a significant role in determining the symbol period; therefore this section discusses the impact of the sampling speed on the CO-OOFDM signal transmission performance. Numerical simulations are carried out by adopting 64 sub-carriers and setting the ADC's quantisation bit resolution and the clipping ratio to be 10 and 13 dB, respectively. Fig. 4 illustrates the data rate against the link span for 64 and 128 sub-carriers, symbol length of 6.4 and 12.8 ns and two sampling speeds of 6.25 and 12.5 giga sample/s (GS/s). Doubling the symbol length increases the link span, particularly at lower data rates. For a symbol period of

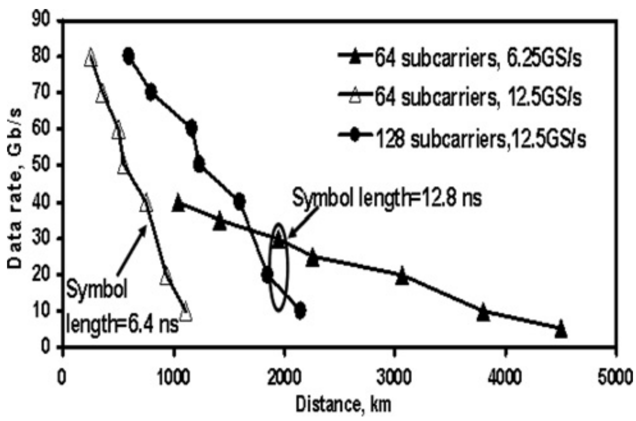

Figure 4 *Data rate against the link span for 64 and 128 sub-carriers, sampling speeds of 6.25 and 12.5 GS/s and symbol length of 6.4 and 12.8 ns*

12.8 ns and at low data rates, adopting a sampling speed of 6.25 GS/s can increase the dispersion tolerance by an average factor of 1.5 compared with the case with a sampling speed of 12.5 GS/s. However, at lower sampling speeds, higher-order modulation formats could be used to achieve the same data rate as that of higher sampling speed. This can be explained as follows. For a fixed symbol length, at lower sampling speed, the number of high frequency sub-carriers that could be used is reduced, and consequently, this results in a lower $OSNR_{min}$ requirement for a specific modulation format adopted for a sub-carrier. At a data rate of 40 Gbps, adopting a sampling speed of 12.5 GS/s is more effective in combating fibre dispersion than at 6.25 GS/s. This is due to the requirement of utilising high-order modulation formats such as 256QAM with a 6.25 GS/s sampling rate compared with 16QAM with a sampling rate of 12.5 GS/s. For 64 sub-carriers, utilising a sampling speed of 6.25 GS/s can increase the dispersion tolerance by a factor of 2.5 when compared with a sampling rate of 12.5 GS/s. This is due to the increased CP length as a result of increased symbol period as well as decreased signal bandwidth.

Considering the SMF non-linearities, Fig. 5 illustrates the data rate against the link span for the symbol length of 6.4 and 12.8 ns for 64 and 128 sub-carriers, respectively. For the data rates >10 Gbps, reducing the sampling speed does not improve the transmission capacity against the reach performance. However, at lower sampling speeds, where the spacing between the sub-carriers is reduced, four-wave mixing (FWM) effects become prominent.

5 Adaptive CO-OOFDM

CO-OOFDM sub-carrier signals will experience amplitude distortion, which depends on the frequency response of the transmission link; consequently, certain sub-carrier components will endure higher distortion than others. To address this problem, CO-OOFDM with the adaptive modulation (CO-AMOOFDM) applied to all sub-carriers is proposed, in which low- and high-order modulation formats are used for sub-carriers with higher and lower distortions, respectively. As a direct consequence of this,

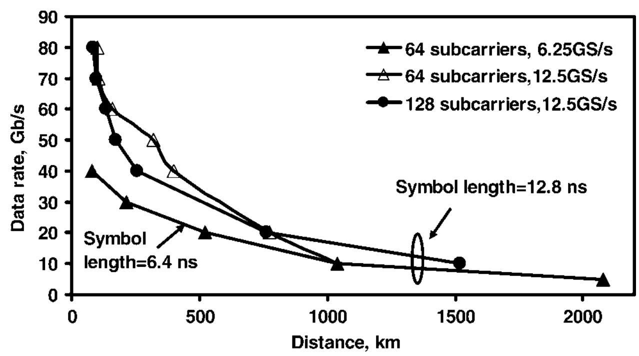

Figure 5 *Effect of the sampling speed on the transmission performance over SMF links*

doi: 10.1049/iet-map.2009.0280

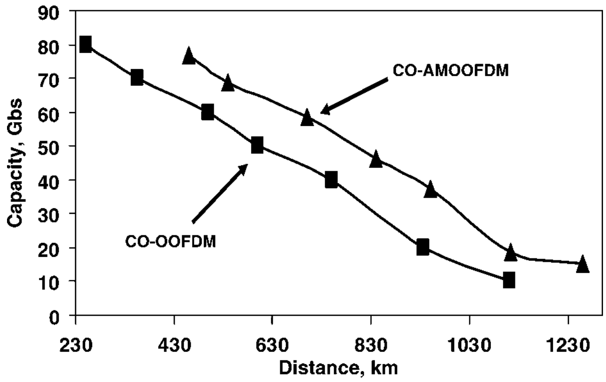

Figure 6 *Data rate against the link span for CO-OOFDM identical and adaptive modulation formats*

the CO-AMOOFDM technique has a unique feature of effectively utilising the entire transmitted signal spectrum. Fig. 6 depicts the data rate against the link span for CO-OOFM with identical and adaptive modulation formats adopted for all sub-carriers while considering only the CD effect. The latter scheme displays an increase in the link span by a factor of 1.4. In contrast, when considering both fibre non-linearities and dispersion, Fig. 7 illustrates the advantage of utilising CO-AMOOFDM over the traditional CO-OOFDM scheme. At lower link span (<280 km), both schemes offer similar data rates. However, at higher link spans, CO-AMOOFDM offers an average improvement of 1.15 times that of CO-OOFDM. Here, the authors have focused on adaptive modulation schemes that improve spectrum usage efficiency, thus resulting in higher tolerance to the CD when compared with the case in which identical modulation formats are adopted across all the sub-carriers.

5.1 ADC parameters

This section presents simulation results to show the effect of ADC/DAC parameters on the transmission performance of CO-OOFDM signals first for data rates up to 80 Gbps over an SMF link while considering only the dispersion effect and secondly for data rates up to 40 Gbps over an SMF link while considering both dispersion and non-linearities. Fig. 8 depicts the data rate against the link span for a range of ADC/DAC bit resolutions for a very high clipping ratio of 13 dB. At higher data rates (e.g. 80 Gbps), higher bit (up to 9) resolution results in increased link span by a factor of 2. However, increasing the bit resolution beyond 9 does not lead to a further increase in the link span. At lower data rates (<20 Gbps), there is no gain in employing higher bit resolution ADCs. Lower bit resolution ADCs would be the best option, but at the cost of increased non-Gaussian quantisation noise levels. The clipping effect on the CO-OOFDM signal is illustrated in Fig. 9 for ADCs with a high bit resolution of 10. For a given data rate, the lower clipping ratio reduces the OSNR as a direct result of increasing the clipping noise effect, which therefore leads to a reduced transmission span. Fig. 9 shows that the optimum clipping ratio is data rate-dependent; moreover, it is shown that for a given data rate, adopting the optimal clipping ratio of 13 dB improves the link span by a factor of 1.34 when compared with the case with a lower clipping ratio of 7 or 8 dB.

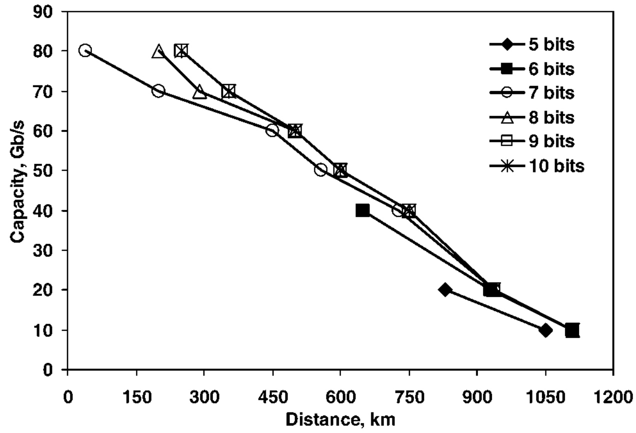

Figure 8 *Data rate against the link span for a range of ADCs bit resolution for a CO-OFDM system*

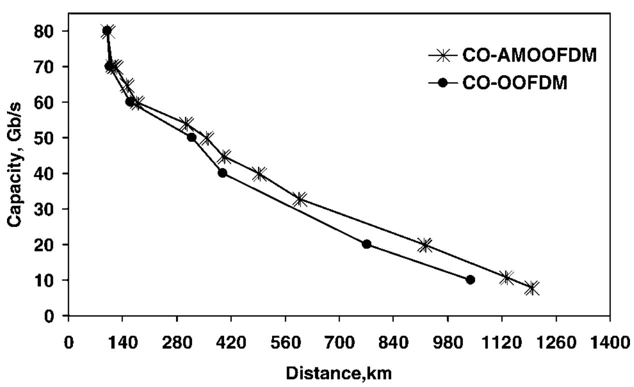

Figure 7 *Data rate against the link span for CO-OOFDM identical and CO-AMOOFDM formats in the presence of fibre non-linearity*

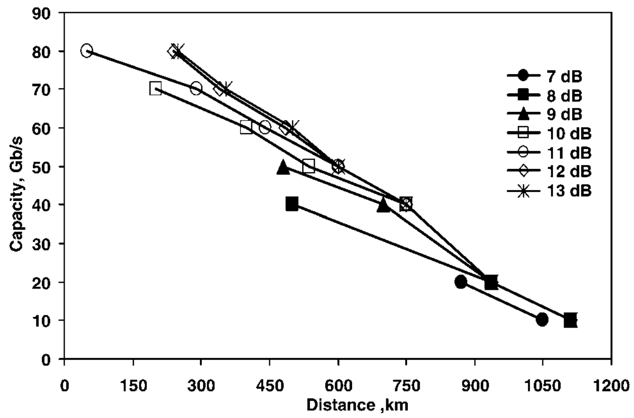

Figure 9 *Capacity against the link span for a range of clipping ratios*

IET Microw. Antennas Propag., 2010, Vol. 4, Iss. 5, pp. 651–658
doi: 10.1049/iet-map.2009.0280

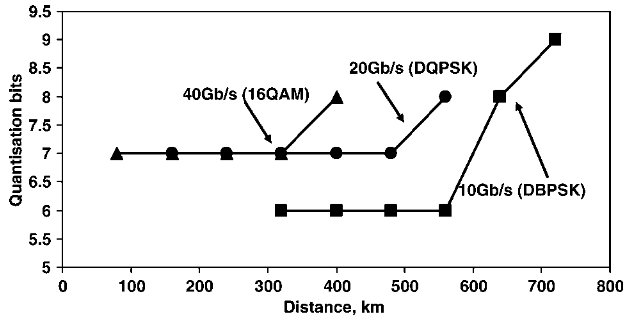

Figure 10 *Quantisation bit against the transmission distance for different data rates*

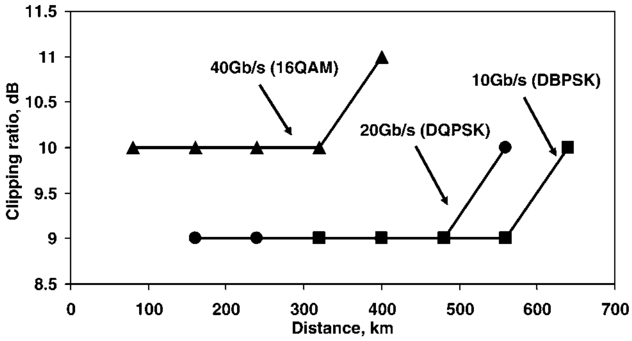

Figure 11 *Clipping ratio against the transmission distance for different data rates*

To illustrate explicitly the transmission distance-dependent optimum ADC parameters, while transmitting over the SMF links considering both impairments CD and fibre non-linearity, the minimum optimum quantisation bit and the clipping ratio are plotted in Figs. 10 and 11, respectively, as a function of the transmission distance for different signal bit rates up to 40 Gbps. Here, the minimum optimum quantisation bits (clipping ratio) refer to as a minimum value corresponding to the $OSNR_{min}$ observed for a specific transmission link. As shown in Figs. 10 and 11 for all data rates, there exists a threshold level beyond which the optimum quantisation bits and the clipping ratio increase exponentially at a rate of 1 bit and 2 dB per 100 km, respectively. Figs. 10 and 11 also show that the fibre length threshold decreases with an increase in the signal data rate. This is because of the accumulated effects of various noise sources mainly due to EDFAs and FWM.

6 Conclusions

For CO-OFDM modems, in comparison with the OFDM employing a long CP, the use of a large number of sub-carriers is more effective in combating the fibre CD. For a fixed number of sub-carriers, dispersion tolerance can also be increased by increasing the CP length from 25 to 100%, which can improve the dispersion tolerance by a factor of 2.7 for lower data rates of up to 25 Gbps. The authors have shown that with the SMF non-linearities, adopting 64 sub-carriers can increase the transmission distance when compared with 32 and 128 sub-carriers. ADC sampling speed plays a significant role in determining the symbol period. Reducing the sampling speed can increase the symbol length and limit the number of high frequency components from propagating along fibres, which increases the CD tolerance. However, for a fixed symbol length, a lower sampling speed does not necessarily lead to CD improvement, as higher order modulation formats are needed to achieve the same data rate as the higher sampling rates. Moreover, reducing the sampling speed further reduces the spacing between sub-carriers, thus resulting in increased FWM effect.

The authors have shown that adaptive modulation schemes have a unique feature of effectively utilising the entire transmitted signal spectrum, thus addressing the amplitude distortion experienced by all the CO-OOFDM sub-carrier signals. It has been shown that the link span increases by factors of 1.4 and 1.2 for dispersion only and both dispersion and fibre non-linearities, respectively.

7 References

[1] HANZO L., NG S., KELLER T., WEBB W.: 'Quadrature amplitude modulation: from basics to adaptive trellis-coded, turbo-equalised and space-time coded OFDM, CDMA and MC-CDMA systems' (IEEE Press, John Wiley & Sons, 2004, 2nd edn.)

[2] Nippon Telegraph and Telephone Corporation, Photonics Laboratories: 'Optical orthogonal frequency division multiplexing (optical OFDM)', 3 November 2003, p. 1

[3] TANAKA Y., KOMINE T., HARUYAMA S.: 'A basic study of optical OFDM system for indoor visible communication utilizing plural white LEDs as lighting'. Proc. Eighth Natl Conf. on Symp. Microwave and Optical Technology (ISMOT 2001), Montreal, Canada, 2001, pp. 303–306

[4] SHIEH W., BAO H., TANG Y.: 'Coherent optical OFDM: theory and design', *Opt. Exp.*, 2008, **16**, (2), pp. 841–859

[5] LOWERY A.J., ARMSTRONG J.: '10 Gb/s multimode fiber link using power-efficient orthogonal-frequency-division multiplexing', *Opt. Exp.*, 2005, **13**, (25), pp. 10003–10009

[6] JANSEN S.L., MORITA I., TAKEDA N., TANAKA H.: '20-Gb/s OFDM transmission over 4160-km SSMF enabled by RF-pilot tone phase noise compensation'. OFC Anaheim, CA, 2007, paper PDP15

[7] LOWERY A.J., DU L.B., ARMSTRONG J.: 'Performance of optical OFDM in ultralong haul WDM lightwave systems', *IEEE J. Lightwave Technol.*, 2007, **25**, (1), pp. 131–138

[8] CAVALLARI M., FLUDGER C.R.S., ANSLNW P.J.: 'Electronic signal processing for differential phase modulation formats'. OFC/TuG2, February 2004, pp. 23–27

doi: 10.1049/iet-map.2009.0280

[9] BRENDON J.C., LOWERY A.J., ARMSTRONG J.: 'Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM', *IEEE J. Lightwave Technol.*, 2008, **26**, (1), pp. 196–203

[10] FÄRBERT A., LANGENBACH S., STOJANOVIC N., *ET AL.*: 'Performance of a 10.7 Gb/s receiver with digital equaliser using maximum likelihood sequence estimation'. Proc. 30th European Conf. on Optical Communications (ECOC 2004), Stockholm, Sweden, September 2004, paper Th4.1.5

[11] ROBERTS K.: 'Electronic dispersion compensation beyond 10 Gb/s'. Dig. 2007 IEEE LEOS Summer Topical Meetings, Portland, Oregon, USA, 23–25 July 2007

[12] LI T., KAMINOW I.: 'Optical fiber telecommunications IVB' (Academic, San Diego, CA, 2002), Ch. 13

[13] WEBER C., FISCHER J.K., BUNGE C.A., PETERMANN K.: 'Electronic precompensation of intrachannel nonlinearities at 40 Gb/s', *IEEE Photon. Technol. Lett.*, 2008, **18**, (16), pp. 1759–1761

[14] HELLERBRAND S., HANIK N., WEIERSHAUSEN W.: 'Optical metro networks and short-haul systems', *Proc. SPIE*, 2009, **7235**, pp. 72350E–72350E-16

[15] LOWERY A.J.: 'Fibre nonlinearity pre- and post-compensation for long-haul optical links using OFDM', *Opt. Exp.*, 2007, **15**, (20), pp. 12965–12970

[16] SHIEH W., ATHAUDAGE C.: 'Coherent optical orthogonal frequency division multiplexing', *IEE Electron. Lett.*, 2006, **42**, pp. 587–589

[17] SHIEH W., CHEN W., TUCKER R.S.: 'Polarization mode dispersion mitigation in coherent optical orthogonal frequency division multiplexed systems', *IEE Electron. Lett.*, 2006, **42**, pp. 996–997

[18] TANG Y., HO K.P., SHIEH W.: 'Coherent optical OFDM transmitter design employing predistortion', *Photon. Technol. Lett.*, 2008, **20**, (11), pp. 954–956

[19] GIACOUMIDIS E., TANG J.: 'Improved transmission performance of adaptively modulated optical OFDM signals over MMFs using adaptive cyclic prefix'. OECC/ACOFT, July 2008, pp. 1–2

[20] LY-GAGNON D., KATOH K., KIKUCHI K.: 'Unrepeated 210-km transmission with coherent detection and digital signal processing of 20-Gbs QPSK signal'. Tech. Dig. OFC 2005, Anaheim, CA, USA, paper OTuL4

[21] SIMEONE O., BAR-NESS Y., SPAGNOLINI U.: 'Pilot-based channel estimation for OFDM systems by tracking the delay-subspace', *IEEE Trans. Wirel. Commun.*, 2004, **3**, (1), pp. 315–325

[22] LOWERY A.J., WANG A., PREMARANT M.: 'Calculation of power limit due to fibre nonlinearity in optical OFDM systems', *Opt. Exp.*, 2007, **15**, (20), pp. 13282–13287

doi: 10.1049/iet-map.2009.0280